

# Mineralogical, Chemical, and Isotopic Heterogeneity in Zagami: Evidence for a Complex Petrogenesis. L. E. Nyquist<sup>1</sup>, K. Misawa<sup>2</sup>, C-Y. Shih<sup>3</sup>, T. Niihara<sup>3,5</sup>, J. Park<sup>4,5</sup>.

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## Introduction:

Textural variations in the shergottite Zagami were initially interpreted as evidence that it formed in a heterogeneous lava flow [1, 2]. Variations in initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between a Coarse Grained (CG) and a Fine Grained (FG) lithology [3,4] and evidence for more extensive fractionation of the Rb/Sr ratio in a Dark Mottled Lithology (DML) [2, 5] are consistent with such an interpretation. More recently, Niihara et al. [6] and Misawa et al. [7] have reported the mineralogy and Sr-isotopic systematics of an Olivine Rich Lithology (ORL) found in association with the coarse-grained DML lithology in the Kanagawa Zagami specimen [6,7]. Here we call this lithology DML(Ka) to maintain a distinction with DML(USNM) as studied by [2]. An Ar-Ar study by Park et al. [8] of a late stage K-rich melt enriched in  $\text{K}_2\text{O}$  to ~7% and intruded into ORL yielded an Ar-Ar age of  $202 \pm 7$  Ma. The present work extends the study of Kanagawa Zagami to Nd-isotopes.

## Alkali (e.g., Rb) and REE (e.g., Sm) abundances:

Distinguishing features of the Kanagawa Zagami lithologies are their enrichments in trace elements compared to so-called Normal Zagami. Even the Dark Mottled Lithology (DML (Ka, 05)) that is host to the volumetrically smaller ORL (~1  $\text{cm}^3$  in .54) appears to be somewhat enriched in Sm compared to the CG and FG Normal Zagami lithologies and a DML subsample obtained from the US National Museum specimen USNM 6545 (Fig.1).

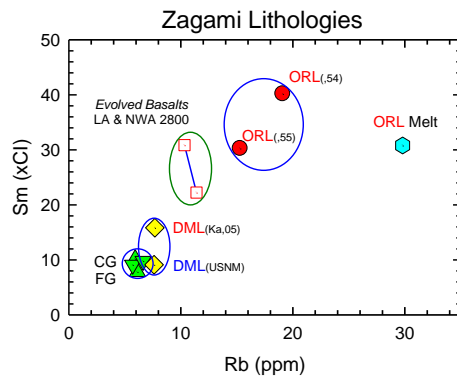


Figure 1. Sm and Rb abundances in Zagami lithologies. CG and FG are Normal Zagami lithologies, DML was obtained from the US National Museum USNM 6545, courtesy of T. McCoy. DML (Ka,05) was sawdust from cutting the DML end of Kanagawa Zagami and contains ~5% admixture of ORL. ORL(.55) was sawdust from cutting ORL, whereas ORL(.54) was a bulk (WR) sample of subsample .54 used for isotopic studies. ORL Melt was an ~9 mg portion of the dark, late-stage, K-rich melt found in association with ORL.

(Our DML sawdust sample .05 is estimated to contain ~5% ORL admixture). ORL and “ORL Melt” are enriched in Sm and other REE by about fourfold compared to the Normal Zagami lithologies. The Rb enrichments in ORL are somewhat smaller. ORL Melt found in association with ORL occurs as dark clusters a few  $\text{mm}^3$  in volume associated with ORL. Its ~4X enrichment compared to Normal Zagami in the subsample used for isotopic studies is accompanied by an even greater enrichment in K in this lithology. K was found to be heterogeneously distributed in eight subsamples of ~42-315  $\mu\text{g}$  studied for Ar-Ar chronology. The material in those samples had crystallized mostly to pyroxene containing irregular areas of enrichment in K and/or phosphate [8].

## Heterogeneity in initial $^{87}\text{Sr}/^{86}\text{Sr}$ :

Studies in 1995 and repeated in 2006 [3,4] showed FG Normal Zagami to have a significantly higher initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio than CG Normal Zagami (Fig. 2). A 2010 study of DML from USNM 6545 showed it to have the same initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio as CG [5], but the Rb-Sr study of ORL by [7] yielded initial  $^{87}\text{Sr}/^{86}\text{Sr}$  lower than in CG, providing further evidence of heterogeneity in the initial Sr-isotopic composition among different lithologies.

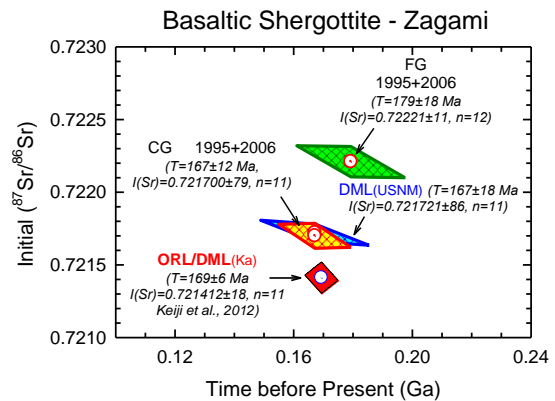


Figure 2. Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. Rb-Sr isochron age for Zagami lithologies.

## Heterogeneity in initial $^{143}\text{Nd}/^{144}\text{Nd}$ :

Fig. 3 shows Sm-Nd-isotopic data for ORL(Ka, .55) and DML(Ka, .05) sawdust, ORL Melt, and subsamples of ORL (Ka, .54). The data for the two sawdust samples are nearly identical, consistent with differentiation of ORL from its host DML(Ka), although ORL is greatly enriched in trace elements (Fig. 1). As expected, WR1, a bulk sample of ORL(Ka, .54) also shares very similar Sm-Nd isotopic data. WR2(l), a leachate of a second whole rock (bulk) sample has only a slightly lower  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio, as expected if most of the REE are

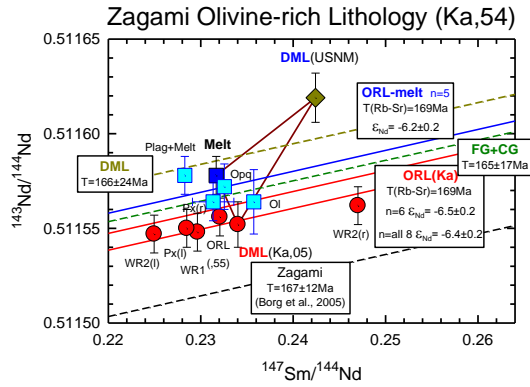


Figure 3. Sm-Nd data for ORL and ORL Melt. Red circles: Bulk samples and leachates, except for WR2(r). Dark blue square: ORL Melt. Light blue squares: density separates. Light green diamond: Bulk analysis of DML(USNM) [5].

in easily leachable phosphate minerals. However, the residue after leaching (WR2(r)) has a lower  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio than expected, suggesting that phosphates were not totally removed in the leaching process. ORL is observed petrographically to contain coarse-grained merrillite, probably the phosphate mineral contributing most REE to the leachates. These data are slightly displaced beneath an  $165 \pm 17$  Ma reference isochron calculated from the combined data for (FG+CG) Normal Zagami (Fig 4).

The data for ORL Melt and mineral separates are displaced towards higher  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios than for the whole rock and leachate samples. Mineral separation was by heavy liquids. (Plag+Melt) of density  $< 2.85 \text{ g/cm}^3$  was observed to contain a significant melt component. "Px" of density  $2.85\text{--}3.7 \text{ g/cm}^3$  was observed to contain pyroxene, melt, and phosphates. This sample was leached in 2N HCL for 10 min. to generate a leachate "Px(l)" and residue "Px(r)". "Ol" of density  $3.7 \text{ g/cm}^3$  was observed to contain olivine and melt. "Opq" was observed to contain opaque minerals like spinel. Of these samples, the Sm-Nd data for the leachate Px(l) plots close to the bulk sample WR1 and the leachate WR2(l). However, Px(r) and Opq have  $^{147}\text{Sm}/^{144}\text{Nd}$  that are very close to that of ORL Melt and much higher REE abundances than expected. Most of the

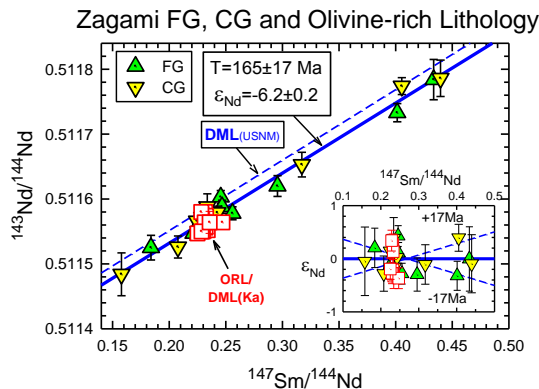


Figure 4. Sm-Nd data for combined CG, FG, ORL, and ORL Melt.

Sm and Nd in these samples came from melt contaminants. Melt was observed in thin section to intrude maskelynite and elsewhere in ORL. The K-rich melt was observed to contain fine-grained phosphates, which would contribute REE to these samples.

As shown in Fig. 5, in spite of the similarity in initial  $^{87}\text{Sr}/^{86}\text{Sr}$  between DML and CG, initial  $^{143}\text{Nd}/^{144}\text{Nd}$ , expressed as  $\epsilon_{\text{Nd}}$ , was found to be slightly higher in DML than in FG and CG [5]. In this study, we find  $\epsilon_{\text{Nd}}$  of both DML (Ka) and ORL to be slightly lower than in CG and FG, but perhaps within uncertainty of the value for these Normal Zagami samples. The disagreement between the  $\epsilon_{\text{Nd}}$  values of DML(USNM) and DML(Ka) is puzzling, but suggests (a) "high" and variable  $^{143}\text{Nd}/^{144}\text{Nd}$  in DML, and (b) some contribution from DML to ORL Melt. Sawdust DML(Ka) has some contribution from DML, also.

Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  more strongly distinguishes among shergottite lithologies than do the  $\epsilon_{\text{Nd}}$  values, and also distinguishes DML(Ka) from DML(USNM). The high initial  $^{87}\text{Sr}/^{86}\text{Sr}$  in FG normal Zagami is slightly lower than that measured for Shergotty, whereas the lower initial  $^{87}\text{Sr}/^{86}\text{Sr}$  for ORL is slightly greater than that of Los Angeles (Fig. 5).

#### Conclusions:

Localized differentiation was important in producing the variety of lithologies observable in Zagami. Heterogeneity in initial Sr- and Nd-isotopic compositions and initial trapped  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios close to the Martian atmospheric composition [8] and possibly relict radiogenic  $^{40}\text{Ar}$  suggest that complex models are required to understand the petrogenesis of Zagami and other enriched shergottites. Such models may involve magma recharge, magma mixing, and crustal assimilation occurring in an upper crustal magma chamber.

**References:** [1] McCoy T. J. et al. (1992) GCA, 56, 3571-3582. [2] McCoy T. J. et al. (1995) LPS XXVI, 925-926. [3] Nyquist L. E. et al. (1995) LPS XXVI, 1065-1066. [4] Nyquist L. E. et al. (2006). Meteorit. Planet. Sci., 41, A135. [5] Nyquist L. E. et al. (2010) Meteorit. Planet. Sci., 45, A154. [6] Niihara T. et al. (2012) 75<sup>th</sup> Ann. Met. Soc. Mtg., Abst #5075. [7] Misawa K. et al. (2012) 75<sup>th</sup> Ann. Met. Soc. Mtg., Abst #5190. [8] Park J. et al. (2013) LPS XXXIV, abs. 2556.

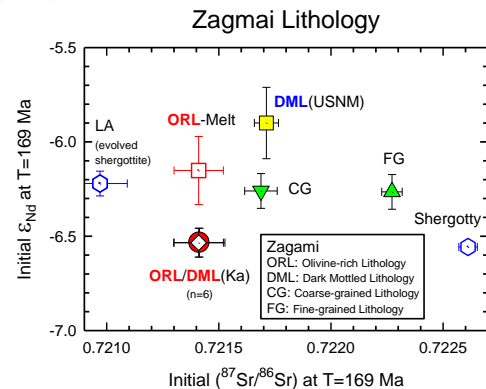


Figure 5. Summary of initial  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\epsilon_{\text{Nd}}$  values in Zagami lithologies for an age of 169 Ma.